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Frozen barrier evolution in saturated porous media

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Abstract

A numerical model capable of simulating the freezing of aqueous solution flow in saturated porous media is presented. This model is based on a finite-difference approximation of the coupled equations for liquid water flow, heat and solute transport and phase change. The phase change equation facilitates the condition for the special case when liquid water and ice can reside in the pore space simultaneously, leading to a 'mushy' zone. Results are presented to show the evolution of multiple frozen regions growing by a chain of freezing pipes. Two different regimes for the evolution of frozen bodies are distinguished based on system parameters. For the regime with lower freezing rate separate frozen bodies exist at steady-state, while for higher freezing rate the regime is characterized by linked frozen bodies. The numerical solution for the first regime is tested by a semi-analytical solution for the case of fresh water. For the second regime the model is able to simulate the process up to the point when linking of the separate frozen bodies occurs. For both regimes freezing is hindered downgradient of the freeze pipe where solute becomes highly concentrated, and a wedge of unfrozen media forms. For the first regime the wedge eventually forms into a liquid 'island' surrounded by ice-bearing porous media.

Keywords: Soil freezing; Frozen barrier; Mushy zone; Numerical modeling

1. Introduction

The freezing of saturated geological material is a technology that can be applied beneficially to solve problems faced in groundwater contaminant remediation and in construction activities. One particular application involves the isolation of a saturated region from the main groundwater flow by using a series of vertical freezing pipes to produce a line of linked frozen bodies essentially impermeable to groundwater flow [1,2]. Prediction of the process of frozen barrier formation and the design of mechanical/thermal systems to produce a frozen barrier involves the specification of equations for fluid flow, heat and solute transport, and phase change. These equations are rather complicated, therefore, most research efforts to date have studied the equations under simplifying assumptions.

The equilibrium shape of a frozen body grown by a freeze source in an air-free porous medium saturated by fresh water was studied by Goldstein and Reid [3] and in series of publications by Kornev et al. [4–6]. They formulated the problem by classical mathematical approach called here the *Stefan model*, and applied a complex variables technique to develop a semi-analytical solution.

The Stefan model is based on the presence of a sharp interface dividing the whole domain on two subdomains: the unfrozen ice-free and the fully frozen water-free region. It is known from the literature [7–10] that in reality there exists an interfacial zone, with ice and liquid being present in the pore void, sandwiched between the fully frozen region and the unfrozen region. This interfacial zone is produced by the variation in freezing temperature, such variation being due to capillary effects [8,11] or osmotic potential effects [10,12]. The osmotic potential effect is seen, for example, during the solidification of binary solutions [9,13,14]. A full model of freezing should incorporate the effects of both capillarity and osmotic potential, as both forces will have a significant

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